EXPERIMENTAL RESEARCH STUDIES ON TOOLS FOR EXTRAVEHICULAR MAINTENANCE IN SPACE

Phase II Final Report

Contract NASW-1590

MAN-SYSTEM INTEGRATION BRANCH (RBM)
BIOTECHNOLOGY AND HUMAN RESEARCH DIVISION
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

August 31, 1967

Report 67-9

Raff ANALYTIC STUDY ASSOCIATES
912 THAYER AVENUE, ■ SILVER SPRING, MARYLAND ■ PHONE: AREA CODE 301—588-8170
ZIP CODE 20910

EXPERIMENTAL RESEARCH STUDIES ON TOOLS FOR EXTRAVEHICULAR MAINTENANCE IN SPACE

PHASE II FINAL REPORT

Report No. 67-9

Contract NASW-1590

Submitted to

Man-System Integration Branch (RBM)
Biotechnology and Human Research Division
Office of Advance Research and Technology
National Aeronautics and Space Administration
Washington, D. C., 20546

Prepared by:

Lawrence B. Johnson

Lawrence B. Johnson

Paul W. Havener

Paul W. Havener

31 August 1967

Raff Analytic Study Associates, Inc.
912 Thayer Avenue
Silver Spring, Maryland, 20910

ACKNOWLEDGMENT

The contributions of Andrew Green and Stanley Lebow of this Company to this study are greatly appreciated.

In addition, our Consultant, Dr. Alphonse Chapanis of the Johns Hopkins University, provided stimulating suggestions for this research. The responsibility for conducting and evaluating the research must remain with the senior author.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

EXPERIMENTAL RESEARCH STUDIES
ON TOOLS FOR EXTRAVEHICULAR
MAINTENANCE IN SPACE

ABSTRACT

This research program was designed to evaluate breadboard models of two conceptual space tool designs developed in an earlier phase of this effort. The basic concept was to develop a multipurpose power tool that would offer suit and glove protection to the space maintenance worker, a unique storage arrangement for tool attachments, and would be compatible with currently envisioned space maintenance tasks.

Two major research and development approaches were undertaken simultaneously. First, tool modifications and accessory development continued throughout the research program based on human, mechanical, and electrical engineering requirements. Second, five behavioral experiments were conducted to evaluate human performance while performing simulated maintenance tasks.

The behavioral and engineering findings suggest further development of a power tool with its power source located at the maintenance operator's elbow. With the use of lightweight metals, a judicious design of the handle mechanism and the interior compartment, it is felt that a highly manageable tool can be developed.

Although the behavioral data were collected by the use of simple simulation devices, performance decrements similar to

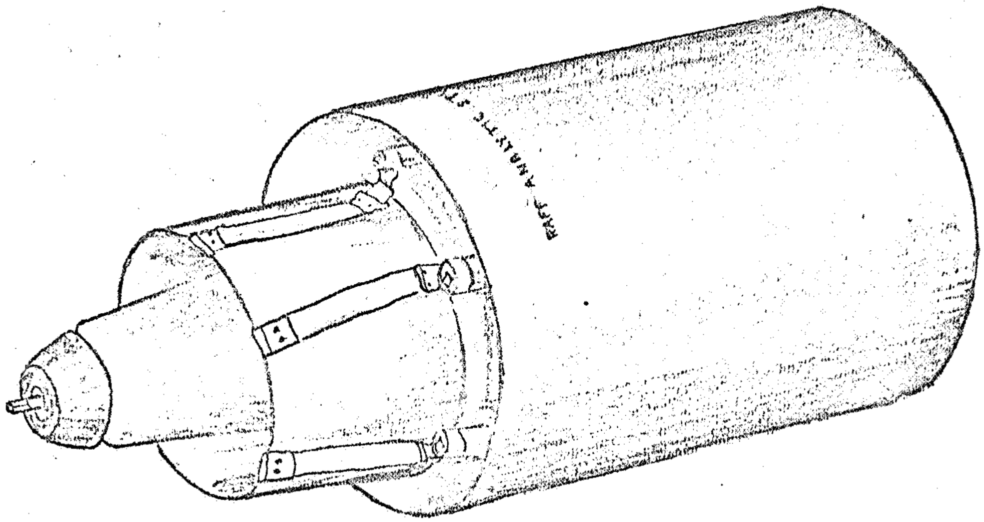
those observed by operators in frictionless environments did occur when the maintenance task cylinder was suspended and permitted to move freely. The experimental trials using the suspended task cylinder indicated many tool characteristics that would not have been observable under purely static conditions.

I -- INTRODUCTION

Raff Analytic Study Associates has conducted a research program on space maintenance concepts and tools for the National Aeronautics and Space Agency since December 1966. The major purpose of the three phased research program was to develop tool mitten concepts for possible use in extra-vehicular activities (EVA) and to review existing literature on maintenance performance decrements resulting from weightlessness and pressure suited conditions.

The initial research effort, described in the Phase I Final Report: Research Program on Tools for Future Manned Space Flights, 27 March 1967, was to develop operating breadboard models of tool mitten concepts and to prepare a paper on maintenance performance decrements resulting from weightlessness and pressure suited conditions (Johnson, 1967). The "space-tool mitten" designation has been adapted to include both developed tools, the space mitten and the tool mitten.

Each of these tools is a multipurpose power tool that can function as an impact wrench, a screwdriver, and as a drilling tool. The tool mitten (Figure 1) is characterized by a cylindrical metal structure that has storage sites for tool attachments emplaced within annular wells toward the face of the tool. Tool attachments can be exchanged by merely pulling a particular attachment out of its well and then mating it to the chuck of the tool mitten. Each attachment is restrained by a flexible metal clockspring and slip ring. The space mitten (Figure 2) originally planned for bare-handed operation, has its motor near the



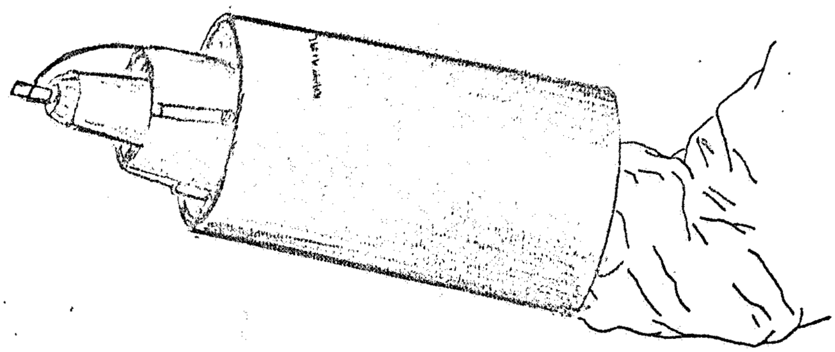


FIGURE 1. -- Tool Mitten Developed During Phase I effort.

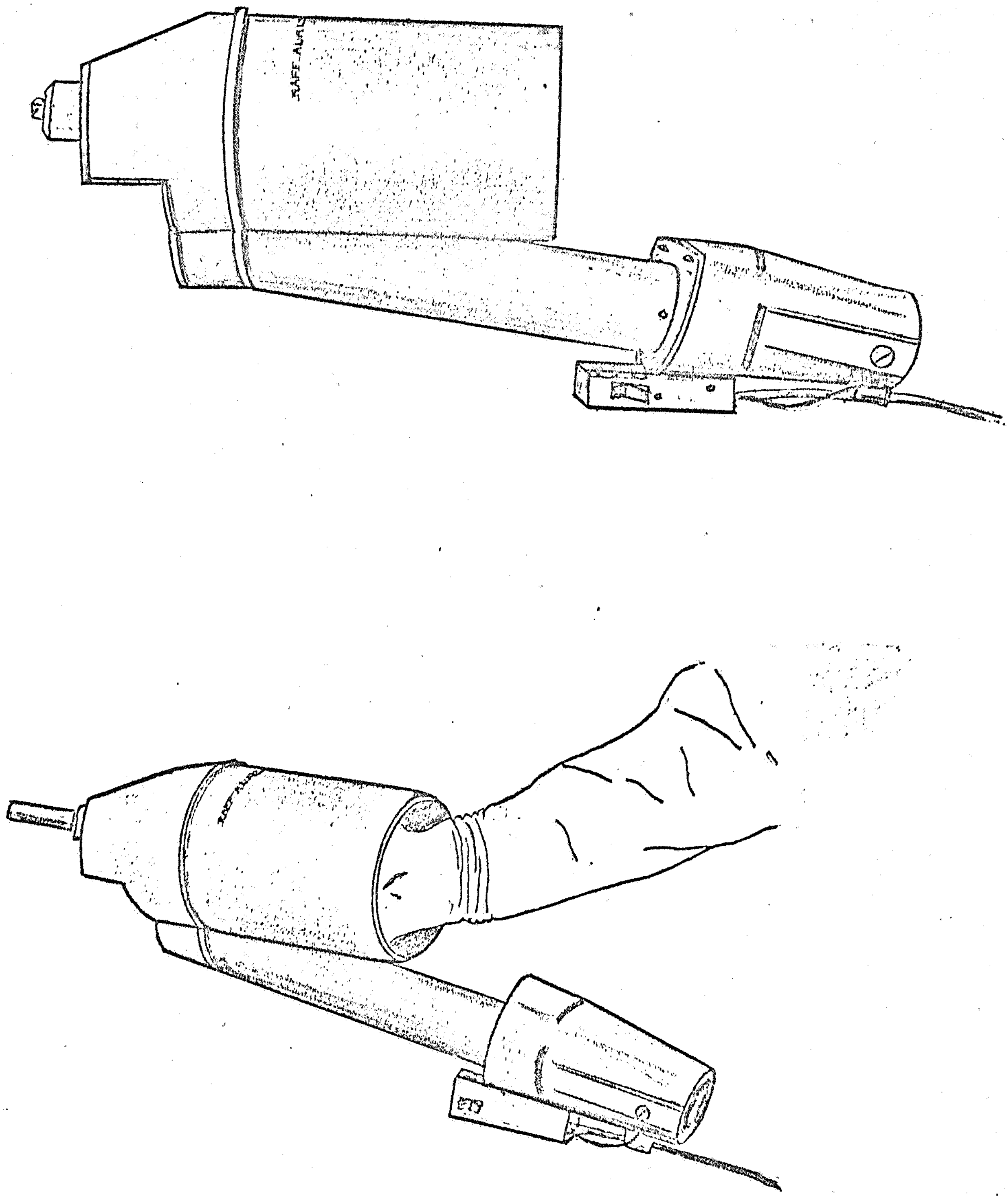


FIGURE 2. -- Space Mitten Developed During Phase I effort.

maintenance worker's elbow. A tool attachment storage site called a tool cuff, an accessory for the space mitten and pictured in Figure 3, is used for the storage of hex sockets and screwdriver attachments.

Two maintenance task assemblies, a maintenance panel and a maintenance task cylinder, described in Johnson, et al (1967), were developed for use in five of the six experimental evaluations. Both the maintenance panel (partially seen in Figure 10) and maintenance task cylinder (partially seen in Figure 4) were employed in the static (stationary) mode. However, the maintenance task cylinder was also suspended from a spring (dynamic model) that permitted 5 degrees of freedom. The maintenance task cylinder was modified during Phase II, as depicted in Figure 4, to accommodate a simulated hatch on a spacecraft. Thirty-six, 1/2 inch hex bolts, 2-1/2 inches apart, were placed around the periphery of the hatch.

A review of studies of maintenance task performance under pressure suited and weightlessness conditions revealed a wide range of performance decrements as compared to unsuited, 1 g conditions. (Johnson, 1967)

The collection of studies involving tool usage indicates that the most important contributing factor to improving maintenance performance under frictionless conditions is the degree in which the worker is attached to his worksite. Under similar frictionless conditions, investigators have indicated performance decrements on the order of 25 to 30 percent, and sometimes higher,

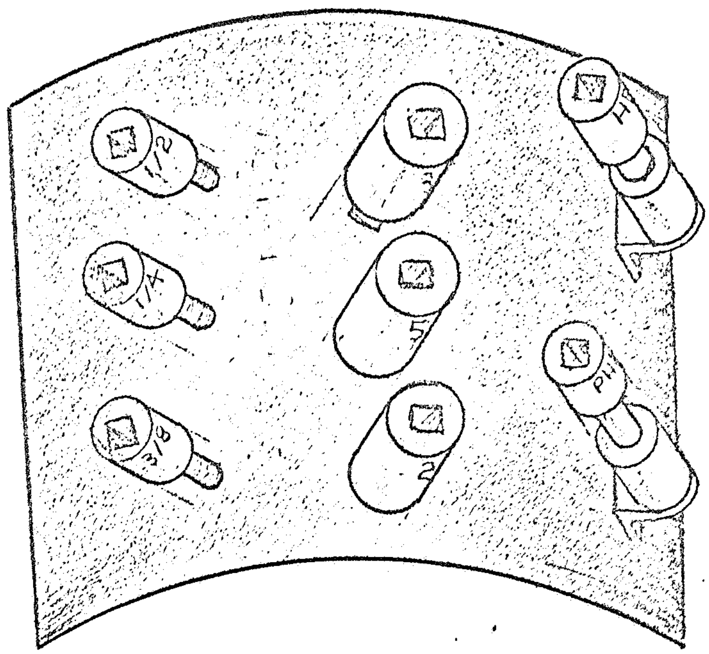


FIGURE 3. -- Tool Cuff (Tool Attachment Storage Sites)

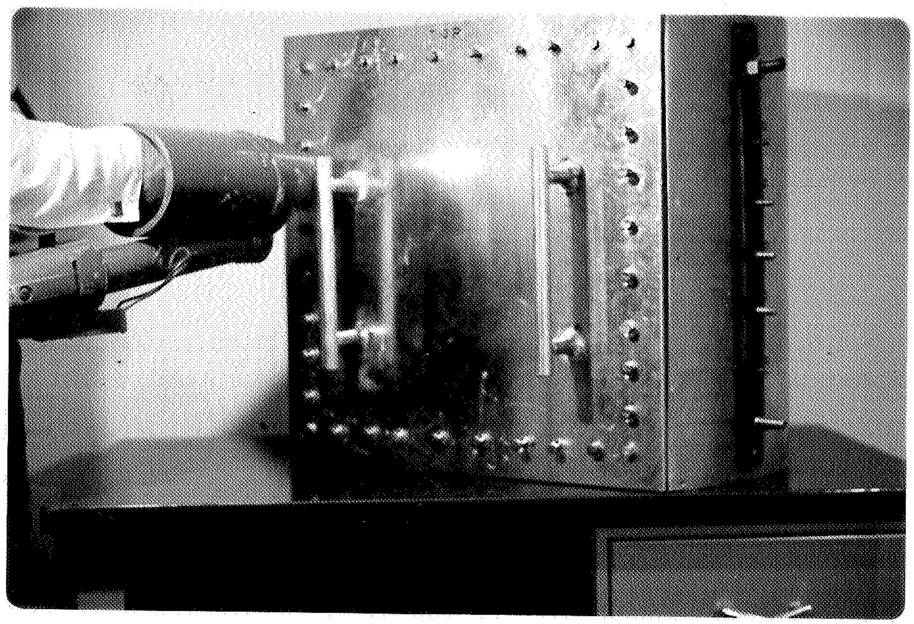


FIGURE 4 -- Hatch Assembly: Maintenance
Task Cylinder (Experiment 3)

in the amount of torque workers can apply under frictionless conditions. However, when these same workers are attached to the worksite or when using hand holds, their performance under the experimental conditions often only decreases 17 percent or less. One study relating to the effect of wearing a pressure suit on torquing with various tools indicated a decrement of 9 to 15 percent when the subjects wore the unpressurized suit. Further performance decrements on the order of 16 to 17 percent resulted when the suit was pressurized.

These studies have reflected the current interest of investigators in developing tethering devices and attachments to be used by space maintenance workers while performing extra-vehicular activities.

The studies involving various maintenance tasks involving several tools under conditions of weightlessness and pressure suit encumbrance indicate the following conclusions. A reasonably stable 30 to 40 percent decrement in performance is noted when the maintenance worker is encumbered with an unpressurized space suit, however, when the worker is performing the same maintenance tasks in the pressurized space suit, performance decrements often exceed 100 percent. These tremendous time increases under the pressurized suit condition result from the reduced mobility and dexterity of the worker, and from the inaccessibility of the components the worker needs to manipulate. Under the weightlessness conditions experienced by workers in simulated environments, it appears that proper positioning of the worker in relationship to his worksite and the attachment of the individual to the worksite are two critical factors that need to be considered in the design and development of maintenance tasks.

It is apparent that the goal for developmental EVA tool use must be to alleviate the performance decrements associated with pressure suit wear and weightlessness. Since the space worker will be restricted in mobility and dexterity, one solution to efficient tool design is to combine several operations into one, thereby relieving the worker for critical activities. An example of this goal is the design of space-tool mittens that not only provide the space worker suit-glove protection, but also allows for rapid tool attachment exchanges. Further, these tools are designed to allow the operator to gain greater access to work areas by the relocation of the tool motor away from the working end of the tool.

The major objective of the Phase II research program, conducted by Raff Analytic Study Associates under Contract NASW-1590, was to evaluate the space-tool mitten concept by performing a variety of human factors experiments under shirt-sleeve, 1g conditions. The experiments were planned and conducted with the aim of gaining insight that could be applied to the pressure-suited space maintenance worker who would perform extravehicular maintenance and assemble tasks in a zero g environment. The major objective has been fulfilled in that the findings and conclusions of these evaluations indicate the feasibility of developing an operating prototype space mitten for engineering evaluation within NASA's own space simulation facilities.

The basic philosophy of this evaluation was to identify and correct design deficiencies in the initial breadboard models by using human factors experiments and engineering analyses. These research studies were performed in order to develop firm requirements for an operating protype space tool.

The research program was a joint engineering development and experimental effort. Even though engineering development and experimental efforts are generally performed sequentially, experience has shown that the two efforts complement each other. However, it was not always possible to separate the rationale for re-tooling on the basis of mechanical or electrical deficiencies, or on the requirements of the human operator for comfort, safety, and visibility. Therefore, some compromises in rigorous experimental control were made because of emergency tool repair. These particular occasions are documented in the report under the specific experimental study.

The experimental program consisted of five small experiments identified by the following designations:

1. Space-Tool Mittens
2. Manual Tools
3. Hatch Test
4. Screwdriving
5. Access Area Study

The experiments dealt with the following variables:

1. Space and Tool Mittens
2. Static and Dynamic Modes of the Maintenance Task Assemblies.
3. Varieties of Hand Tools
4. Varieties of Maintenance Tasks

In addition, a qualitative, modified critical incident evaluation was made of the performance of maintenance workers using the space mitten with the tool cuff, and using the tool attachments of the tool mitten. These comments are included in the Engineering Evaluation, Section VII. Each of the experiments are discussed in detail below.

The detailed presentation and interpretation of the statistical analyses are presented in Appendix A for Experiments 1-4.

II -- EXPERIMENT 1: SPACE-TOOL MITTENS

An evaluation of the tool mitten and space mitten was conducted to determine the decrement in operator performance when the worksite (maintenance task cylinder) was unstable relative to the worker. This dynamic mode simulated, to some extent, space workers performing maintenance tasks with elusive worksites in under zero or reduced gravity conditions.

2.1 Procedure.

2.1.1 Subjects. Eight junior college students, ranging in age from 18 to 23, were used as experimental subjects. These subjects took part in the experiments for an average of $1\frac{1}{2}$ hours a day, twice a week, for approximately six weeks. Because of equipment breakdowns and modifications, as well as availability of the subjects, a completely random assignment of subjects was impossible. Further, the results are reported only for those subjects who completed all the experimental trials. For the cases in which all eight subjects did not complete the experimental series, a note is made in the various graphs of operator performance.

2.1.2 Task. Each subject was required to tighten five hex bolts of the same size (3/4, 5/8, 9/16, 1/2, and 7/16 inch hex head diameters) into a metal bar containing embedded, welded nuts. The embedded nuts were placed approximately 2 1/2 inches apart. Upon the completion of the tightening task, the subject was instructed to remove five bolts with the power tool.

2.1.3 Instructions to Subjects. This is an experiment which attempts to discover important facts about space maintenance activities. We have a number of tools, conventional and power, that you will be using to torque bolts and nuts onto these devices (work panel or maintenance task cylinder). Before each trial, you will be told which pieces of equipment are to be used. You will be permitted to start the nut or bolt by hand just prior to the time I say begin. The time taken to torque the bolt or nut with a particular tool will then be recorded. In addition, I will record the time it takes you to remove the bolt or nut with the tool. The time measure will begin when I say "begin" and end when either the bolt or nut gives firm resistance to your tightening or when it drops to the floor as you are loosening the nut or bolt.

After the initial instructions were given, the experimenter started each trial by stating "Are you ready? Begin".

The subjects were further instructed to stop torqueing when either the space mitten or tool mitten would slip or stall, or when the manual resistance of torqueing with conventional tools became markedly different.

2.2 Experimental Design. This experiment was planned as a large factorial design in which eight subjects would torque five bolts of the same size under combinations of the following variables:

a. Mode (maintenace task cylinder: static or dynamic)

b. Tools (space mitten or tool mitten)

c. Four trials

d. Tightening or loosening bolts

e. Five different hex head sizes (3/4, 5/8, 1/2, 9/16, and 7/16 inches)

Unfortunately, tool modifications and repairs and subject availability obviated the completion of a full factorial design with randomized ordering of experimental conditions.

If desired comparisons among bolt hex head sizes are made, the differing lengths of bolt shanks and conversely the number of rotations required to tighten and loosen the bolts would become a compounding feature of this study. To avoid this, the approach has been to treat each hex head size as a small factorial experiment. Further, since all subjects did not complete all tests, some bolt hex head sizes are associated with less than eight subjects. In addition, the 3/4 inch hex head data are quite incomplete and therefore are not reported.

Each of the reported hex head sizes was treated as a 2 x 2 x 4 factorial design in which task cylinder mode (static or dynamic), two tools, and four trials were the independent variables. Time to complete either a tightening or loosening task was considered the dependent variable.

2.3 Results and Discussion. The graphical presentation of these data in Figures 5 and 6 indicates a superiority of the space mitten over the tool mitten. The mean time for performing the torqueing task was 23.7 seconds for the tool mitten and 19 seconds for the space mitten. Performance with the tool mitten took approximately 25 percent longer than with the space mitten.

A comparison of the experimental trials conducted under dynamic and static modes of the cylinder revealed a performance time increase of 10.3 percent for the dynamic mode.

A closer look at the interaction of tools and cylinder modes revealed that performance with the space mitten and tool mitten differed by only 3 percent (space mitten 13.9 seconds and tool mitten 14.3 seconds) when the cylinder was in the static mode.

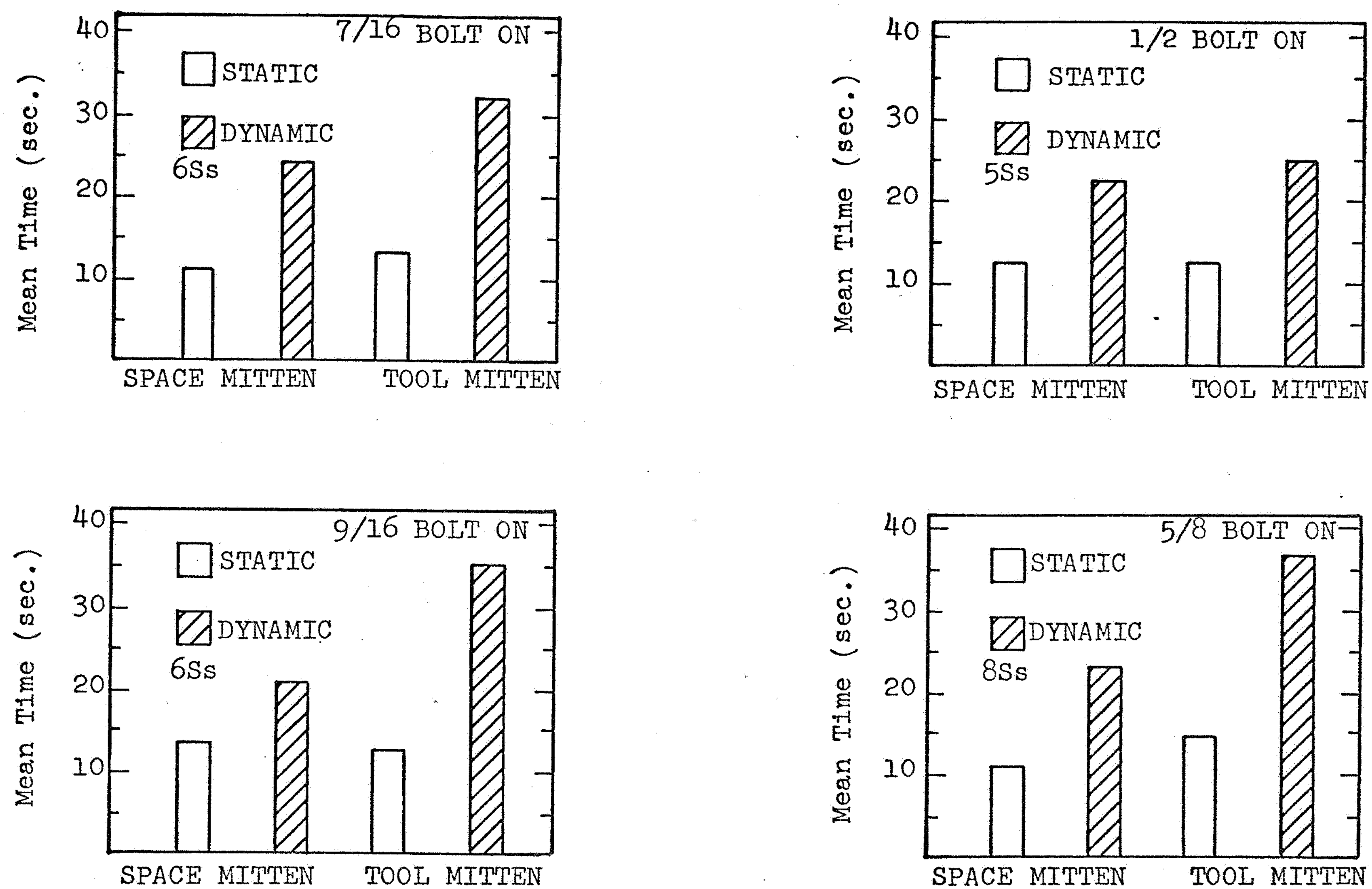


FIGURE 5 : Mean Operator Performance Time as a Function of Space Tool Mitten and Cylinder Mode (Static - Dynamic)

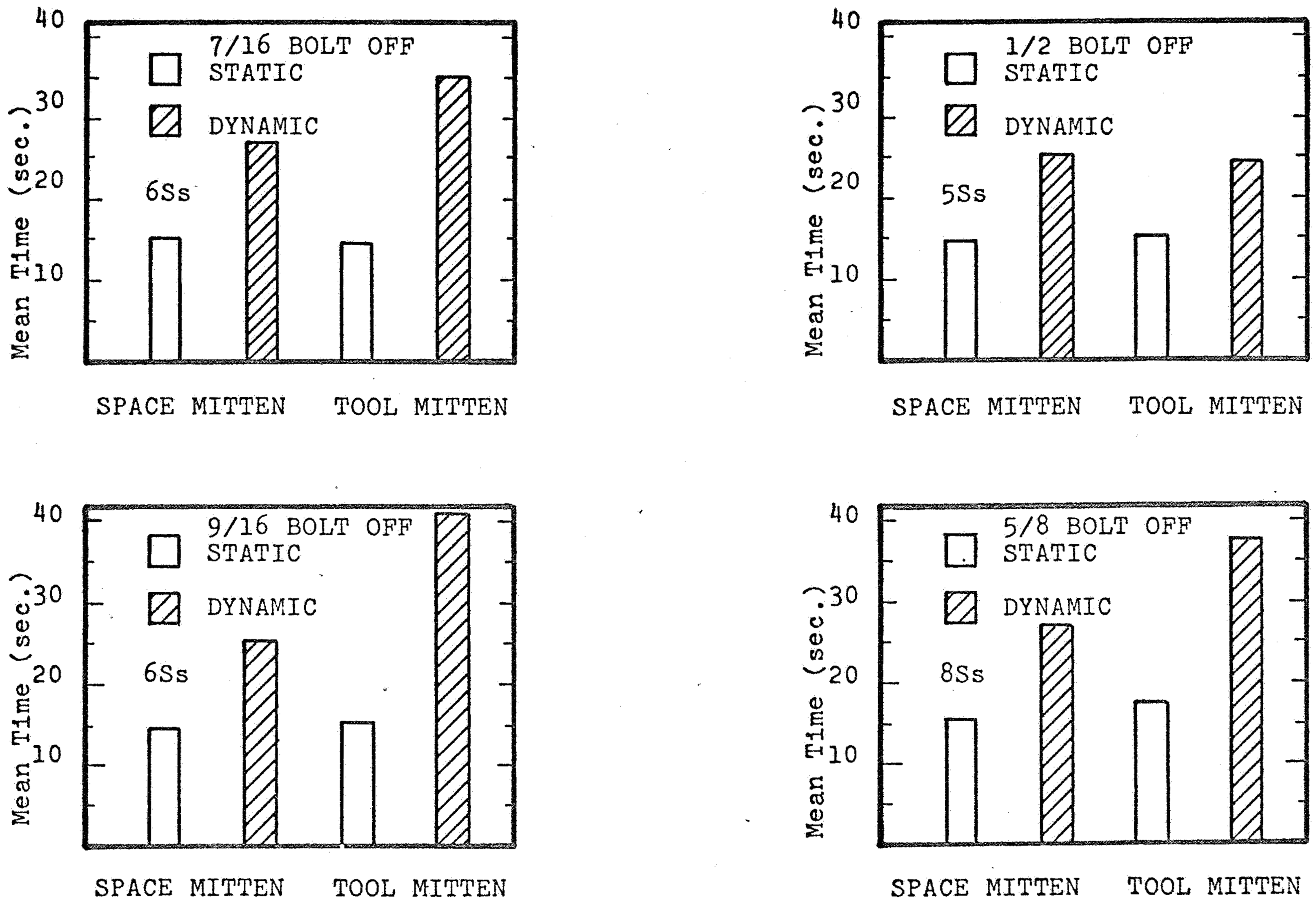


FIGURE 6: Mean Operator Performance Time as a Function of Space Tool Mitten and Cylinder Mode (Static - Dynamic)

On the other hand, in the dynamic mode, performance with the tool mitten took 37 percent longer.

When tool performance is viewed under static and dynamic conditions, operator's performance with the space mitten increased from 13.9 seconds to 24.1 seconds, approximately a 73 percent increase. Performance time under static and dynamic modes for the operators using the tool mitten increased from 14.3 to 33.1 seconds, which is almost a 132 percent increase.

The above results clearly indicate the superiority of the space mitten under task conditions in which the worksite is unstable. Significant learning effects were not observed during the four performance trials.

A detailed discussion of the statistical analyses are presented in Appendix A.

III -- EXPERIMENT 2: MANUAL TOOLS

An evaluation of open and box end wrenches was made to determine operator performance when the same work was performed on different, yet static work sites. Operator performance while tightening and loosening nuts was also compared.

3.1 Procedure. The same general instructions were given to the same eight subjects that participated in the previously described experiment. During these trials, the subjects tightened or loosened nuts (hex head sizes 3/4, 11/16, 1/2, 7/16, and 3/8) on studs embedded in steel and aluminum plates which were affixed to the maintenance task assemblies.

The experiment was planned as a factorial design in which eight subjects would torque five nuts of different sizes with either the open or box end of conventional wrenches. These wrenches are pictured in Figure 7.

3.2 Experimental Design. Each of eight subjects performed four maintenance tasks (trials) under the following variables:

1. maintenance task panel -- maintenance task cylinder
2. tightening or loosening nuts
3. open or box end wrenches.

Subject and tool availability did not permit a completely randomized ordering of experimental conditions. A given experimental trial consisted of either tightening or loosening five different nuts. This experiment has been analyzed as a 2 x 2 x 2 factorial design.

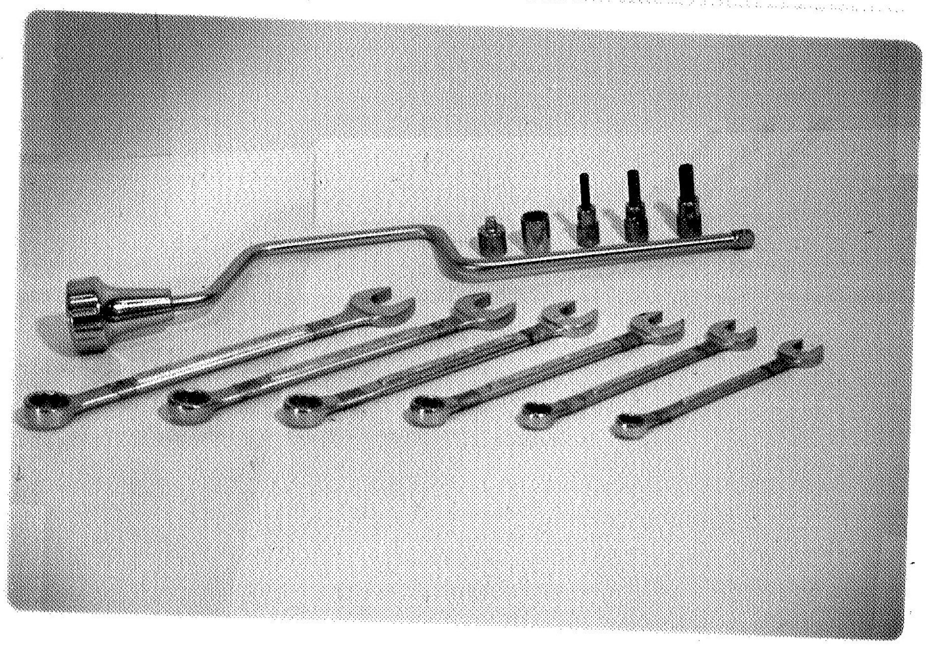


FIGURE 7: Manual Tools

3.3 Results and Discussion. A study of these data do not reflect any major trends. However it does appear that operator performance with the same size bolt on different work sites did differ. Figure 8 reflects the mean time for tightening or loosening (nut on-off) operations, and shows that operator performance with the maintenance task panel took approximately 23 percent longer than with the task cylinder. This overall percentage increase is somewhat misleading because the experiment with the 7/16 hex head nuts did not reflect a difference between worksite performance, whereas the 11/16 hex nut experiment indicated a 66 percent time increase. Since performance time does not increase uniformly, it is quite likely that the observed differences were due to the late introduction of the task cylinder into the experiment.

It can be surmised from Figure 8 that operator performance with the open end wrench on the task panel was approximately 32 percent better than with the box end wrench. Operator performance with the task cylinder, although not statistically significant reflected a slight increase in time for the open end wrench as compared to the box end wrench, the former a mean of 29.8 seconds and the latter, 27.0 seconds.

The superiority of the operator's performance while using the open end wrench as compared with the box end wrench on the panel is not uniformly found for the trials with the cylinder. There seems to be a slight decrement in operator performance with the open end wrench (cylinder trials) as hex sizes increase.

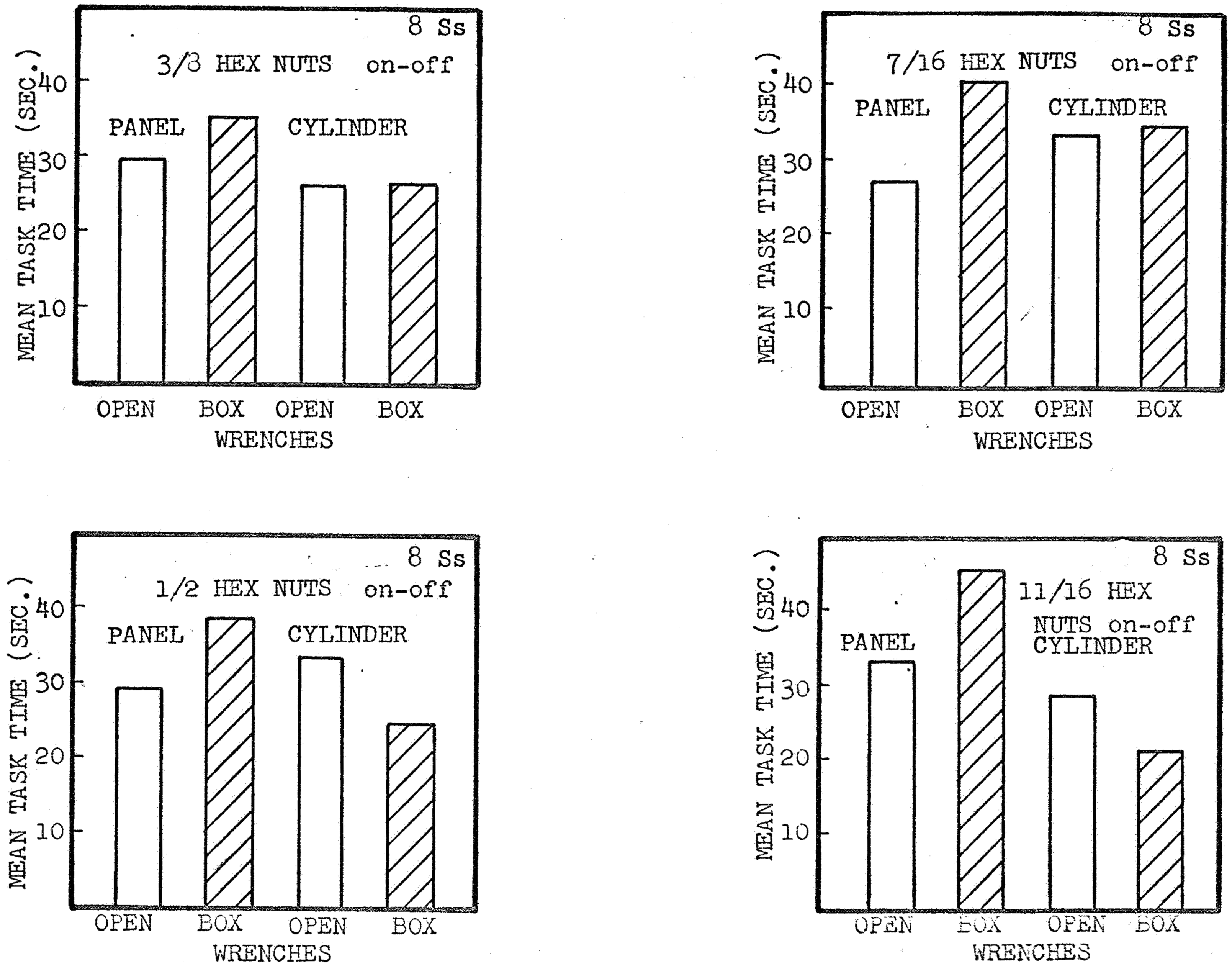


FIGURE 8 - EXPERIMENT 2, MANUAL TOOLS: COMBINED MEAN TIME TO PERFORM MAINTENANCE TASK AS A FUNCTION OF TOOL TYPE AND MAINTENANCE TASK CYLINDER

On many trials the operators used the open end wrench as a forward nut driver, and thus may have improved their performance for the smaller nuts, but not for the larger nuts. Basically these data are somewhat contradictory, and any conclusions must await definite investigations with a wider range of hex nut sizes.

IV -- EXPERIMENT 3: HATCH TEST

A third experiment was conducted in order to evaluate operator performance with the tool mitten and space mitten when the maintenance task cylinder (work site) was in either a static or dynamic mode. These tests were conducted to simulate numerous repetitive tasks that are likely to be encountered by space maintenance workers and to validate the results of Experiment 1 on the static and dynamic modes.

4.1 Procedure.

4.1.1 Subjects. It was felt that more experienced subjects should be utilized as a means of validating previous work done with inexperienced junior college students. Therefore, two Raff Associates personnel, ages 20 and 30 were used as experimental subjects. These subjects were selected because of their experience with these particular tools and their background in engineering and shop work.

4.1.2 Task. The subject was required to tighten 32 of the 36 one-half inch hex bolts that were distributed around the periphery of the hatch shown in Figure 3. (The other four bolts held the hatch in place.) Before the subject tightened all 32 bolts, the experimenter "hand turned" each bolt one-half turn.

4.1.3 Instructions to Subjects. You are to torque each of these bolts into this hatch. Start with the bolt identified on the maintenance task cylinder as "start". Continue to torque in a clockwise manner. The four corner bolts have been installed to keep the hatch on, so you must not attempt to remove those bolts. Remember to stop the power tool the moment the tool begins to slip or stall. Work as quickly as you can.

When I say "begin", start torqueing the bolts going in a clockwise direction, beginning with the bolt indicated as "start".

Are there any questions?

Begin.

4.2 Experimental Design. This experiment was planned as a 2 x 2 x 2 factorial design in which the variables were:

a. The maintenance task cylinder in either the dynamic or static mode

b. Tool mitten versus space mitten

c. Subject 1 versus Subject 2.

The study was conducted as a complete factorial with the assignment of the experimental conditions by Latin Square randomization. Each subject participated in nine blocks of the experiment. Each block consisted of four trials of two tools used each in the dynamic and static modes. Unfortunately, some bolts became cross threaded or damaged during the tests, however, due to the randomization procedure these problems were generally constant for all experimental treatments.

4.3 Results and Discussion. Mean operator performance time with the space mitten and tool mitten was essentially equal, 63.7 seconds and 61.5 seconds respectively, for the hatch fastening operation while the cylinder was in the static mode. Although the statistical test, the analysis of variance, did not reveal a statistically significant difference between the performance of the two tools, an inspection of the dynamic cylinder mode data indicate that the space mitten performance time was 19 percent longer than the tool mitten performance time.

Figure 9 reflects the combined mean performance time of the hatch fastening task completed by the two subjects with both of the space-tool mittens. It is apparent that there was a remarkable difference in the performance of the two subjects. For instance, subject 2 took 62 percent more time to complete the task than subject 1.

Further, Figure 9 indicates that the dynamic mode of the cylinder, with hatch assembly, caused subject 1 to take 262 percent more time to complete the task. In addition, subject 2 took 290 percent more time to perform the hatch task.

It is interesting to note that the decrement in performance noted for the space mitten, when used in the dynamic mode, resulted in a 241 percent increase in time. On the other hand, performance with the tool mitten resulted in a tremendous 321 percent time increase!

These results substantiate those findings noted in experiment 1, however these differences are more striking. The dynamic cylinder mode, as a simulation of a frictionless work environment, seems to offer a reasonable facsimile.

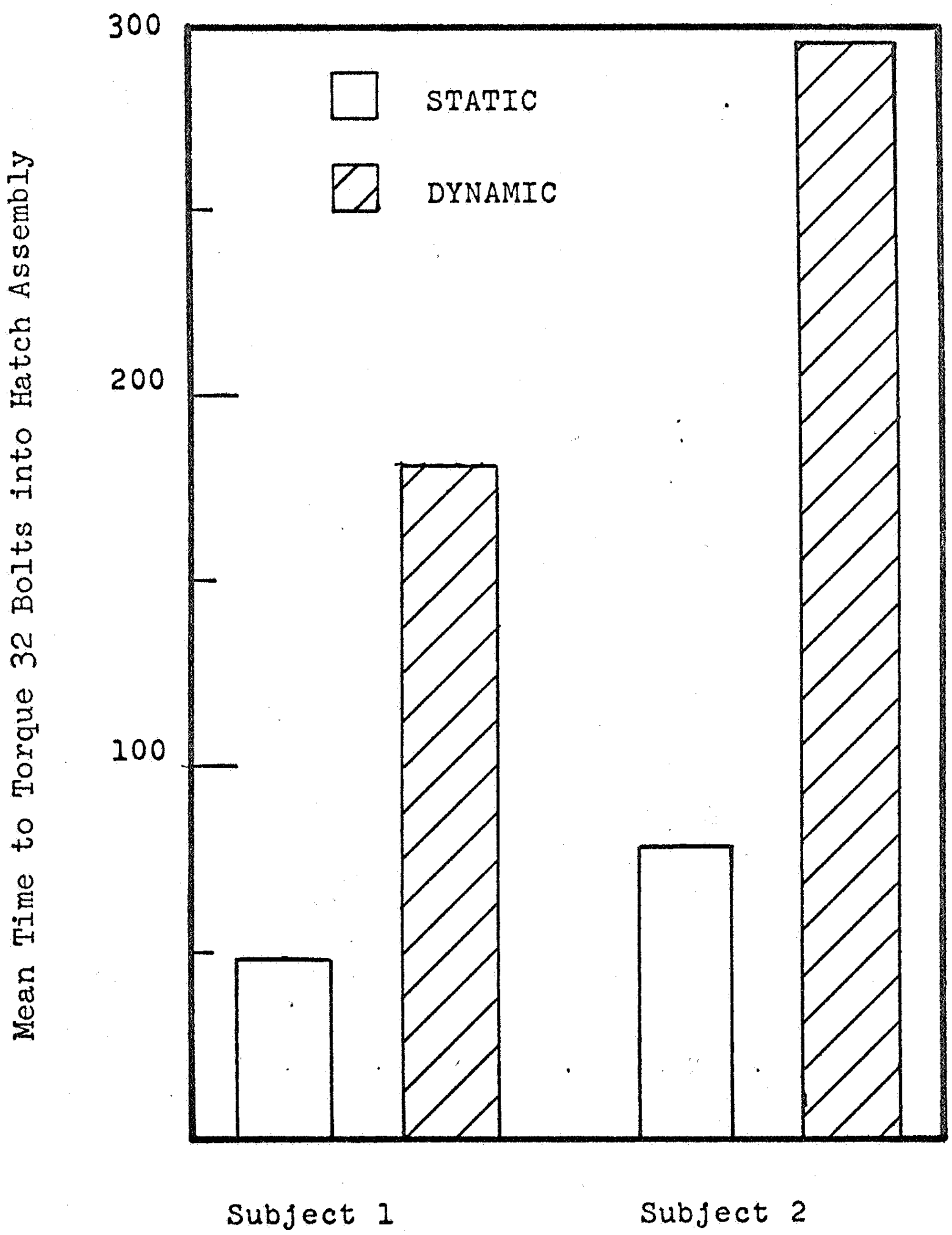


FIGURE 9 : Experiment 3, Hatch Test. Mean Time to Torque 32 Bolts into Hatch Assembly as a Function of Subject and Cylinder Mode (Static-Dynamic)

V -- EXPERIMENT 4: SCREWDRIVING

As part of the overall research plan to evaluate the multipurpose features of the space-tool mittens, this brief experiment was designed to investigate the capability of the space mitten and tool mitten to operate as screwdrivers. In addition, one manual tool, a speeder handle (crank), was used in the investigation.

5.1 Procedure. The same two experienced subjects were used in this experiment that were used in the Hatch Test. The subjects' task was to tighten five recessed Allen screws. Screwdriver bit sizes of 3/16, 1/4, and 5/16 inches were used. The subjects' task was to perform the screwdriving with each of the three Allen tools (space mitten, tool mitten and speeder handle). The particular type of screws used in this experiment are shown in Figure 10. The various plates containing these screws are shown with the static maintenance work panel.

Since the tool mitten's high torque output damaged the nuts and bolts during previous experiments, it was decided to use an auto transformer (Powerstat Variable Auto Transformer Model 116B) to reduce and control the torque. The voltage was lowered from 120 to 70 volts.

The subjects were given the same basic instructions as before regarding torqueing tasks.

5.2 Experimental Design. This experiment was conducted as a 3 x 3 factorial design with Latin's square randomization

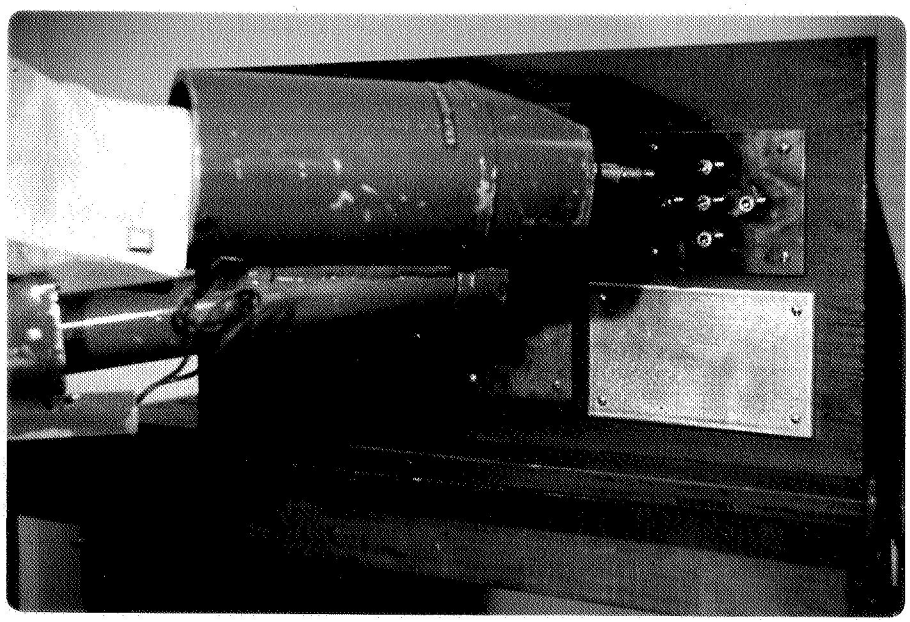


FIGURE 10: One of Three Screwdriving Plates used in Experiment 4, shown on Maintenance Task Panel

of experimental conditions. Two subjects performed the screwdriving tasks with various combinations of tools (tool mitten, space mitten, speeder handle) and three sizes of hex head screws. Each experimental trial employed a particular tool with a particular screwdriving plate. Each subject completed nine trials for each of the nine blocks.

5.3 Results and Discussion. This experiment was performed primarily to view the space and tool mittens as multi-purpose devices. It is graphically shown in Figure 11 that the space mitten was significantly more efficient than the tool mitten or hand-operated crank. The two operators took approximately 61 percent longer to complete the task with the tool mitten than with the space mitten. Further, the use of the hand operated crank resulted in a 141 percent time increase for the performance of these screwdriving tasks.

There is a slight increase in task time as the screw head size increased for the power tools. However, there is a mean reduction of $6\frac{1}{2}$ seconds for the task involving the 5/16 hex head screw with the crank.

It appears from these tests that such multi-purpose functions are well within the realm of capabilities for the next generation of space-tool mittens.

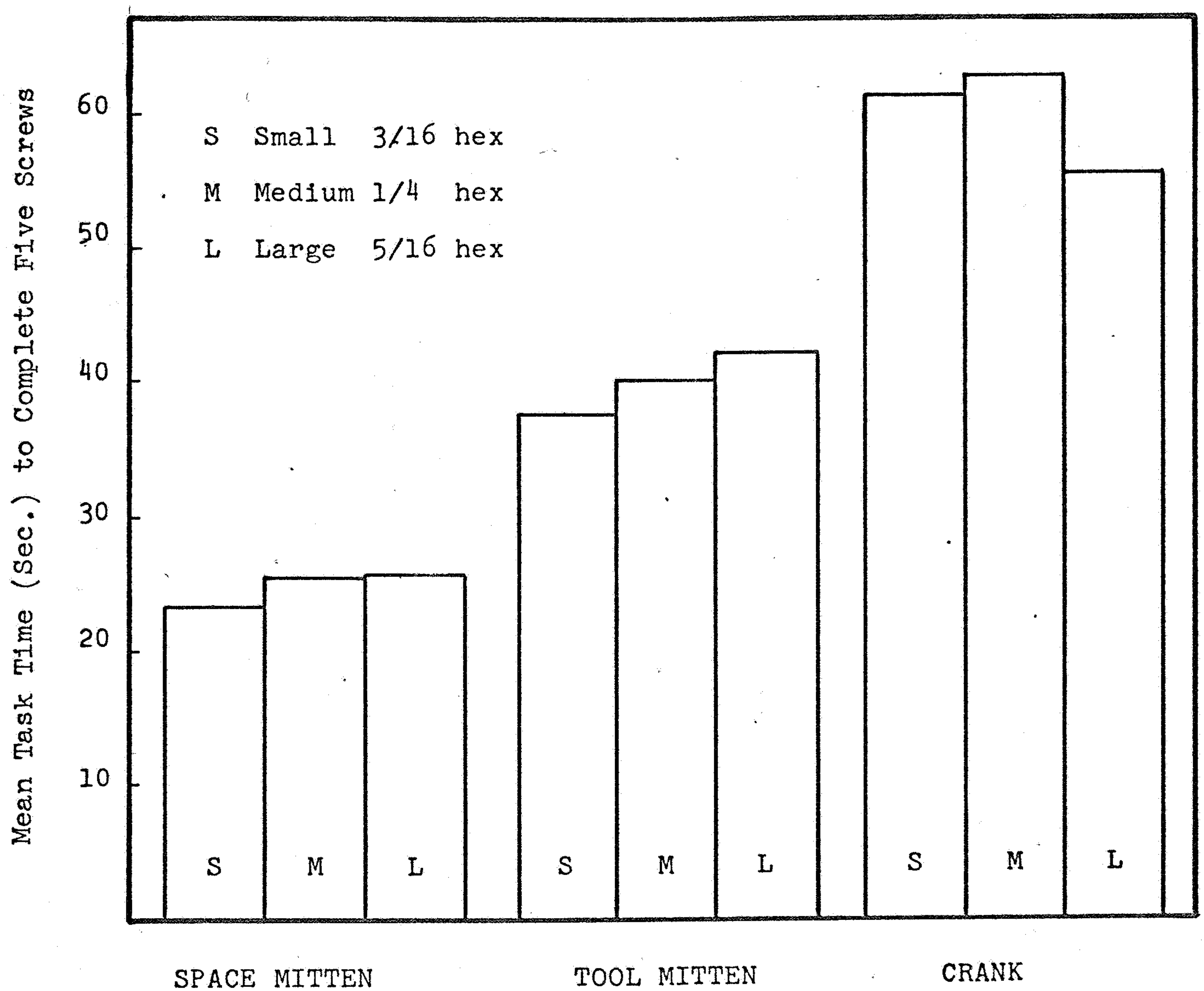


FIGURE 11: Experiment 4, Screwdriving: Task Time as a Function of Screw Size and Tool

VI -- EXPERIMENT 5: ACCESS AREA STUDY

This experiment was conducted to investigate the ease with which various tools could reach simple worksite areas when accessibility to the areas becomes a problem. Kama (1963) and Kennedy and Filler (1966) have investigated the general problem of accessibility for various maintenance tasks.

6.1 Procedure. The two experienced subjects used on previous experiments took part in this study.

6.2 Experimental Design. The subject's task was to pick up each of the tools and attempt to mate the tool with the five Allen screws on the metal plate within each access opening. The plate and the access openings are shown in Figure 12. Further, the subjects were to pick up either the space mitten, tool mitten, Allen key, or speeder handle (Figure 7) in a previously determined randomized order. The subject was not required to actually complete the screwdriving operation but merely to mate the tool with each of the five fasteners. Time was not recorded.

The experimenter randomly presented to the subjects all possible combinations of access apertures and depths. The 3 sets of "egg crate" dividers permitted depths of 6, 9, and 12 inches and overall areas of 8 x 8, 12 x 12, and 16 x 16 square inches. The particular pairings of access depth and access areas were randomly assigned to the nine experimental blocks. Each block consisted of four trials with each of the four tools.

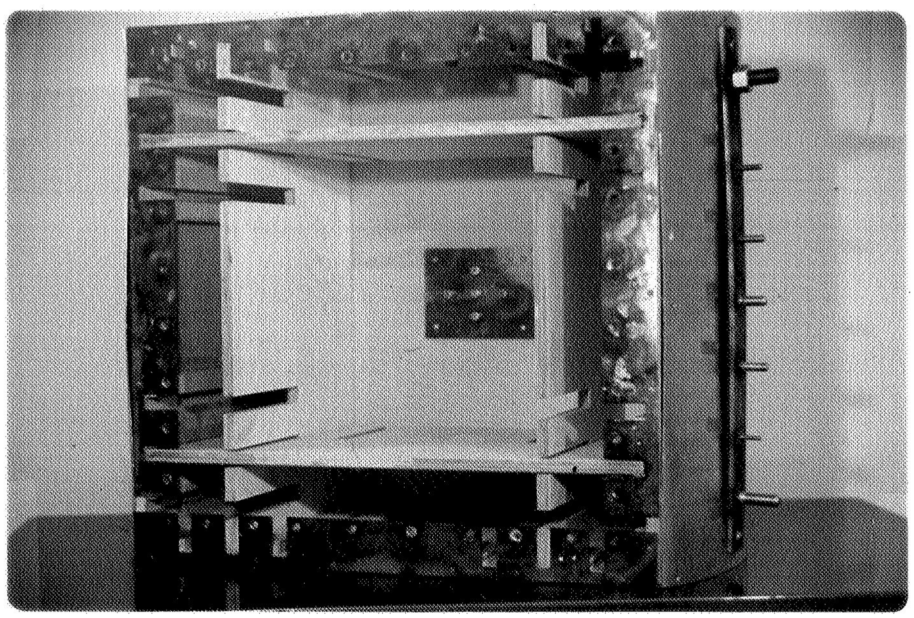


FIGURE 12: Access Area of Maintenance Task Cylinder

Instructions to Subjects -- Imagine that you have a maintenance task to perform in a limited period of time in this access area here (S is shown the maintenance task assembly access area). Further, imagine that you have a choice of four different tools to accomplish this task. I want you to pick up the tool (space mitten, tool mitten, open-end wrench or box-end wrench) that I specify and place the working end of the tool on one of the bolts in the access area. Next, place the working end of the tool on each of the five bolts. Don't be concerned if you experience difficulty in successively placing a tool on each bolt.

After you have followed the above procedure with each of the four tools before you, in the order I have presented them to you, I want you to rank these tools on the ease in which you imagine you could accomplish the maintenance task. That is, ranking the tool, number one, that is easiest, and ranking each successive tool increasing ranks. You may have tied ranks if you choose.

Are there any questions?

Begin.

6.2 Results and Discussion. Based on the preferential ranking of the four tools on nine experimental blocks, the median order of preferences for the four tools is as follows: the Allen key, the speeder handle, the space mitten, and the tool mitten. These preferences are based upon median rankings over all conditions.

This experiment tends to suggest that for screwdriving operations in which recessed hex head screws are used, conventional tools, e.g., Allen head wrenches appear to be more suitable. The choice of a power tool for this function must necessarily depend upon the frequency of these operations that are required. In this experiment, in which only five screws needed to be mated with a particular tool, it appears that the Allen hex head wrench is sufficient.

VII -- ENGINEERING EVALUATION

A number of comments and critical evaluations have been made of the performance of the space mitten and tool mitten in conjunction with the tool cuff, maintenance task cylinder and maintenance task panel. These evaluations have been made by Raff Associates technicians, engineers of various disciplines, scientists, and college students. Many of the evaluations were made following experimental sessions and during various stages of design. The aim of this section is to combine impressions gained during experimentation and design.

The overall concept of a power tool that would offer pressure suit-glove protection has been substantially confirmed. The added advantage of a tool (space mitten) with its power source near the elbow has been confirmed through experimentation and critical engineering evaluations.

7.1 Tool Mitten.

7.1.1. Concept. This tool was developed as an impact wrench-screwdriver from off-the-shelf components. It was designed to provide a source of mechanical power in the performance of extravehicular activities by an astronaut -- maintenance operator. A major feature of this device is a means of storing tool attachments. The tool attachments such as different sized socket wrenches, assorted screwdrivers, are stored in cells around the periphery of the tool mitten and are retained by six spring loaded metal tapes. Such attachments are physically attached to the tool so they will not drift away. The metal straps permit free movement of the sockets from the storage position to the operating position on the tool chuck. It is also possible to select and use different attachments and return them to storage without danger of their drifting away from the operator. The spring loaded clips which grasp the sockets permit the selection of an appropriate mix of attachments by the maintenance worker prior to leaving the parent spacecraft.

7.1.2 Critical Evaluation. The tool mitten, illustrated in Figure 2, was quite bulky and therefore unwieldy. The location of the motor in front of the operator's hand and the location of the tool attachments around the periphery of the tool caused visibility and control difficulties.

Tool attachment exchange was extremely difficult. The retaining ring on the chuck remained quite stiff during the evaluation and caused operators to use a great deal of force in compressing the retaining ring when placing tool attachments on the chuck. Further, the interface between the chuck and tool attachments was improper and resulted in the attachments rocking about on the chuck. Also, the metal strips tended to wrap around the chuck when the tool was in use. Tool attachment exchange is made even more difficult since the length of the tool is such that the operator is not able to effectively use the opposite hand to make the tool exchanges.

A control difficulty was encountered when operating the tool in its reverse mode. Some operators expressed difficulty due to the force required on the trigger to activate the reverse mode.

The tool mitten's torque output was quite excessive for the tasks required in this research program. Often, during the experimental series, nuts and bolts became cross-threaded.

7.1.3 Recommended Solutions. Many of the difficulties encountered with this device were due to the design requirement of using off-the-shelf components. Future generation devices can eliminate many of the above problem areas. For example, a tapered nose could conceivably reduce the bulk at the front of the tool and likely improve controllability and visibility. Further, a collapsing or telescoping cloth or metal outer shell might also result in a reduction of overall bulk and improved operator visibility and controllability.

Possibly a new system of tool exchanges, e.g., spring loaded retrievable cables or telescoping arms could be considered. The current metal strip system is unacceptable.

Previously identified problems such as the reverse switch, high output torque, and the poor chuck and tool attachment interface can be solved by appropriate design efforts.

The concept of the motor in front of the operator's hand (tool mitten) has to be reconsidered in view of the experimental findings and evaluations that indicated better operator performance while using the space mitten.

7.2 Space Mitten.

7.2.1 Concept. This tool is housed in an aluminum cylinder, and is characterized by its power source near the operator's elbow (Figure 2). When originally fabricated, the tool was capable of generating approximately 24 foot-pounds. The motor windings tended to "short" during the extensive testing phase of the research and resulted in a lower torque output. However, heavy use did point out likely failure of components. The tool has a manual (non-ratcheting) override that permits the maintenance operator to make fine torqueing adjustments. Further, this tool is considerably lighter and smaller than the tool mitten previously described.

7.2.2 Critical Evaluation. The overall diameter of the tool was greatly reduced by the introduction of a cantered handle that allowed the operator positive control. The cantered handle is displaced approximately 15 degrees from the vertical and has a cross sectional T-shape as recommended by Holmes (1965). The narrow end of the T fits easily into the V of the thumb. Unfortunately there was not enough space in the handle to contain more than the on-off switch. The reversing switch was placed externally near the motor on the operator's elbow.

Quite a bit of difficulty was noted with the chuck of this tool. Even though several different sized locking ball bearings were used, tool attachments had a tendency to slip off the chuck.

7.2.3 Recommended Solutions. It is quite possible to taper the front structure of the space mitten in order to reduce the size of the structure and to improve visibility and control for the operator. It is felt that a reduction of weight and size can be accomplished while still allowing adequate freedom of motion for the astronaut's gloved hand within the enclosure.

It is further felt that a major reduction in overall weight and bulk can be made by the redesign of the gear train and shaft linkage. In addition, it is now realized that the shifting mechanism for changing the operation of the tool from power mode to manual mode is not desirable because the added weight, bulk, and complexity of the device outweighs the conveniences. It is therefore felt that manual operations are better accomplished with other tools.

Based on our experiments and evaluations of simulated maintenance tasks by persons operating these tools, it is felt that a device with an output of 200 inch pounds would be sufficient for a number of space maintenance tasks. It is also felt that it would be possible to use a rechargeable battery as a power source rather than the a-c current employed in the first generation models. The tool envisioned would be similar to the current tools in that it would operate for torqueing and screwdriving operations. For both of these operations a wide assortment of tool attachments would be available for performing a variety of maintenance tasks.

Furthermore, to keep the bulk and weight of the device within manageable limits, lightweight metals would be considered for the casing and inner workings of the tool.

7.3 Tool Cuff.

7.3.1 Concept. The tool cuff pictured in Figure 4 operates on the principal that the tool attachments will be stored separately from the tool on the maintenance worker's person or on the worksite. However, the storage and removal of tool attachments will require the use of the power tool. The storage sites for the impact wrench sockets are tapered studs containing split captured nuts. Each tapered stud retains a single tool socket; as the socket is emplaced and torqued, the split nut is driven down on the stud, expands and binds the socket. To remove the socket, the operator reverses the tool causing the nut to rise and contract, thus releasing the engaged socket. Allen head, slotted, and Phillips screwdrivers can be held in place by the contraction of the inner walls of the small cylinders, a device similar to collets used on a lathe. Removal of the screwdriver merely allows the internal walls of the cylinder to relax, thereby releasing the tool.

Some difficulty was experienced when using the space mitten to remove and emplace tool sockets on the tool cuff. It was rather easy to cross-thread the locking nut and the screwdriver attachments would sometimes disassemble while the screwdriver was being removed.

7.3.2 Recommended Solutions. The problems envisioned with the tool cuff seemed susceptible to easy solutions. The storage sites for tool attachments could be placed on swivels or other devices in order to allow the maintenance worker more flexibility in retrieving tool attachments. At the present time it is assumed that the tool cuff will be located on the worker's arm or leg. However, the tool cuff can be modified so that it can be stored at the work site.

7.4 Maintenance Task Assemblies. The maintenance task panel and the maintenance task cylinder were quite suitable for simulated worksites for the maintenance experiments. It is realized that these compact and reasonably portable devices are quite useful for investigators who have limited facilities and who do not wish to invest considerable effort and expenses to develop sophisticated simulation facilities. The behavioral data collected suggest that human maintenance performance on untethered worksites do cause operators difficulties that are somewhat similar to those faced in frictionless environments. Therefore, the approach taken is quite useful during the early states of design and development, although it does not have high fidelity. If additional development activities are warranted by these efforts, it is recommended that existing NASA simulation facilities be used in the evaluation of these space tools.

VIII -- CONCLUSIONS

The space and tool mittens have been evaluated extensively. In terms of human performance the space tool appears superior to the tool mitten. Further this superiority is borne out on general tool configuration, controllability, and balance. In addition, the method of tool attachment exchange utilizing the tool cuff is superior to that associated with the tool mitten's peripheral cells. In general, the comparison of the space and tool mitten reflected the superiority of the former in terms of tool use under static and dynamic conditions (Experiments 1 and 3), as a multi-purpose tool (Experiments 1, 3, and 4), and as a tool adaptable to limited areas (Experiment 5).

Under a variety of conditions using power and manual tools, it appears that the dynamic mode of tool operation causes performance decrements that resemble decrements noted under frictionless conditions. It appears that these simple simulation devices are quite useful during early design and development activities to highlight design deficiencies.

The continuing engineering evaluation has provided Raff Analytic Study Associates with a reasonably firm idea for the design and development of a prototype tool that could be utilized in NASA's highly instrumented and well controlled simulation facilities. It is conceivable that the further evaluation of these tool concepts when maintenance operators are fully suited under pressurized and frictionless conditions will be most beneficial.

LIST OF REFERENCES

Burlington, R. S., and May, D. C., Handbook of Probability and Statistics with Tables, Handbook Publishers, Inc., Sandusky, Ohio, 1958.

Holmes, Allen E., Space Tool Kit Survey, Development and Evaluation Program, (Final Report -- Martin Company Report No. ER-13942), 1965.

Kama, W. N., Volumetric Workspace Study, Part I, Optimum Workspace Configuration for Using Various Screwdrivers, (AMRL-TDR-63-68 (I)), August 1963.

Kennedy, K. W., and B. E. Filler, Aperture Sizes and Depths Of Reach for One - and Two - Handed Tasks, (AMRL-TR-GG-27), October 1966.

Johnson, L. B. Phase I Report: A Review of Maintenance Performance Decrements Resulting from Weightlessness and Pressure Suit Conditions, (Raff Analytic Study Associates, Inc., Report No. 66-23), 27 February 1967.

Johnson, L. B., E. R. Wilcomb, S. J. Raff, and P. W. Havener, Phase I Final Report: Research Program on Tools for Future Manned Space Flights, (Raff Amalytic Study Associates, Inc., Report No. 66-24), 27 March 1967.

APPENDIX A

Appendix A presents a detailed statistical treatment and interpretation of the analyses of variance performed on the experimental data previously discussed in the body of this paper. In addition, as overview is given of the F distribution upon which the analysis of variance is based and the sources of variance associated with the analysis of variance. Further, a sample of the raw data is presented.

Statistical Treatment of Experimental Results of Experiment 1: Space - Tool Mittens. The eight analysis of variance tables are presented in this appendix. These tables are identified for each of the bolt sizes. The letter A represents the maintenance task cylinder mode, B, the space mitten - tool mitten used, and C, the number of experimental trials. The data for the 5/8, 7/16, and 9/16 bolts are reasonably consistent. That is, the A X B interaction and A and B main effects are statistically significant beyond the one percent level for these bolt sizes. However, for the 1/2 inch bolt size, only the A variable was statistically significant beyond the one percent level. None of the other effects reflected a statistically significant difference.

The A x B interaction is graphically portrayed in the text in Figures 5 and 6 for bolt on and bolt off respectively. Operator performance with either the space mitten or tool mitten in the static mode does not differ significantly. However, as noted by the cross hatched bars of three of the graphs, operator performance with the tool mitten was significantly poorer than with the space mitten under conditions where the maintenance task cylinder was in the dynamic mode.

The main effect of trial C was not statistically significant. It can be assumed that the number of trials investigated did not reflect any major learning effect.

The experimental results which are of most significance for further tool research can be summed up as follows. The space mitten and tool mitten are essentially equivalent in the static mode, but in the dynamic mode, where the maintenance task cylinder was free to move so as to simulate, to some small degree, frictionless conditions, the space mitten proved to be significantly better.

EXPERIMENT 1

SPACE TOOL MITTEN

TABLE 1

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

7/16 on

ØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	6.20817E+03	1	6.20817E+03	3.92405E+02
B	6.00000E+02	1	6.00000E+02	3.79247E+01
C	8.97083E+01	3	2.99028E+01	1.89009E+00
AB	2.34375E+02	1	2.34375E+02	1.48143E+01
AC	8.97500E+01	3	2.99167E+01	1.89097E+00
BC	7.80833E+01	3	2.60278E+01	1.64516E+00
ABC	5.58750E+01	3	1.86250E+01	1.17725E+00
REM	1.26567E+03	80	1.58208E+01	
TØT	8.62162E+03	95		

TABLE 2

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

7/16 off

ØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	5.95350E+03	1	5.95350E+03	2.04178E+02
B	2.10042E+02	1	2.10042E+02	7.20349E+00
C	5.37500E+00	3	1.79167E+00	6.14461E-02
AB	4.33500E+02	1	4.33500E+02	1.48671E+01
AC	1.90833E+01	3	6.36111E+00	2.18158E-01
BC	7.63750E+01	3	2.54583E+01	8.73107E-01
ABC	1.30417E+02	3	4.34722E+01	1.49090E+00
REM	2.33267E+03	80	2.91583E+01	
TØT	9.16096E+03	95		

EXPERIMENT 1

SPACE TOOL MITTEN

TABLE 3

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

1/2 on

SØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	2.48645E+03	1	2.48645E+03	1.01152E+02
B	2.64500E+01	1	2.64500E+01	1.07602E+00
C	1.76000E+01	3	5.86667E+00	2.38664E-01
AB	2.00000E+01	1	2.00000E+01	8.13628E-01
AC	8.95000E+00	3	2.98333E+00	1.21366E-01
BC	1.25500E+01	3	4.18333E+00	1.70184E-01
ABC	5.00000E+01	3	1.66667E+01	6.78024E-01
REM	1.57320E+03	64	2.45812E+01	
TØT	4.19520E+03	79		

TABLE 4

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

1/2 off

SØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	1.73911E+03	1	1.73911E+03	1.11170E+02
B	1.12500E-01	1	1.12500E-01	7.19137E-03
C	1.24375E+01	3	4.14583E+00	2.65015E-01
AB	3.61250E+00	1	3.61250E+00	2.30923E-01
AC	9.43750E+00	3	3.14583E+00	2.01092E-01
BC	4.92375E+01	3	1.64125E+01	1.04914E+00
ABC	3.63375E+01	3	1.21125E+01	7.74271E-01
REM	1.00120E+03	64	1.56437E+01	
TØT	2.85149E+03	79		

EXPERIMENT 1

SPACE TOOL MITTEN

TABLE 5

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

9/16 on

SOURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	4.63426E+03	1	4.63426E+03	7.18513E+01
B	9.06510E+02	1	9.06510E+02	1.40549E+01
C	1.52115E+02	3	5.07049E+01	7.86147E-01
AB	2.04426E+03	1	2.04426E+03	3.16950E+01
AC	1.11781E+02	3	3.72604E+01	5.77700E-01
BC	5.68646E+01	3	1.89549E+01	2.93883E-01
ABC	4.51146E+01	3	1.50382E+01	2.33158E-01
REM	5.15983E+03	80	6.44979E+01	
TØT	1.31107E+04	95		

TABLE 6

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

9/16 off

SOURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	6.20817E+03	1	6.20817E+03	1.72489E+02
B	1.33504E+03	1	1.33504E+03	3.70931E+01
C	2.09042E+02	3	6.96806E+01	1.93602E+00
AB	1.66667E+03	1	1.66667E+03	4.63070E+01
AC	2.17250E+02	3	7.24167E+01	2.01204E+00
BC	3.77083E+01	3	1.25694E+01	3.49232E-01
ABC	8.47500E+01	3	2.82500E+01	7.84904E-01
REM	2.87933E+03	80	3.59917E+01	
TØT	1.26380E+04	95		

EXPERIMENT 1

SPACE TOOL MITTEN

TABLE 7

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

5/8 on

SØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	9.67788E+03	1	9.67788E+03	1.28452E+02
B	2.37188E+03	1	2.37188E+03	3.14813E+01
C	1.55773E+02	3	5.19245E+01	6.89178E-01
AB	7.45945E+02	1	7.45945E+02	9.90071E+00
AC	1.28648E+02	3	4.28828E+01	5.69171E-01
BC	4.95234E+01	3	1.65078E+01	2.19103E-01
ABC	9.83594E+00	3	3.27865E+00	4.35165E-02
REM	8.43837E+03	112	7.53426E+01	
TØT	2.15779E+04	127		

TABLE 8

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

5/8 off

SØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	8.22403E+03	1	8.22403E+03	1.10320E+02
B	1.31328E+03	1	1.31328E+03	1.76169E+01
C	5.40625E+01	3	1.80208E+01	2.41738E-01
AB	6.12500E+02	1	6.12500E+02	8.21631E+00
AC	5.90312E+01	3	1.96771E+01	2.63956E-01
BC	1.44156E+02	3	4.80521E+01	6.44589E-01
ABC	1.51687E+02	3	5.05625E+01	6.78265E-01
REM	8.34925E+03	112	7.45469E+01	
TØT	1.89080E+04	127		

Statistical Treatment of Experimental Results of Experiment 2: Manual Tools. Analysis of variance tables for these data are presented in this appendix. The statistically significant F ratios for the maintenance panel-cylinder comparison presented in Table 9 were quite likely due to the late introduction of the cylinder into the experimental trials. In general, it appears that the significant A x C interactions, noted in Table 9 and in Figure 8 in the text, indicate that the superiority of the operator's performance while using the open end wrench on the panel is not uniformly found for the trials with the cylinder.

The individual analysis of variance tables for each hex size are presented in Tables 10 - 14.

TABLE 9

STATISTICALLY SIGNIFICANT MAIN EFFECTS

AND FIRST ORDER INTERACTIONS

FOR EXPERIMENT 2

MANUAL TOOLS

SOURCE	Nut Head Sizes in Inches			
	3/8	7/16	1/2	11/16
A (Panel-Cylinder)	X		X	X
B (Tighten-Loosen)				
C (Open-Box End)		X		X
A x B				
A x C		X	X	
B x C	X			

Cells marked X are significant at the .01 Level. The other effects were not found to be statistically significant.

/

EXPERIMENT 2
MANUAL TOOLS
TABLE 10

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

3/4

SOURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	5.41144E+03	1	5.41144E+03	3.59426E+01
B	5.90977E+01	1	5.90977E+01	3.92524E-01
C	1.07511E+04	1	1.07511E+04	7.14083E+01
AB	1.36598E+02	1	1.36598E+02	9.07276E-01
AC	1.41094E+03	1	1.41094E+03	9.37141E+00
BC	8.30160E+02	1	8.30160E+02	5.51389E+00
ABC	5.94141E+00	1	5.94141E+00	3.94626E-02
REM	3.73384E+04	248	1.50558E+02	
TØT	5.59437E+04	255		

TABLE 11

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

11/16

SOURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	1.47622E+04	1	1.47622E+04	1.30937E+02
B	5.62500E-01	1	5.62500E-01	4.98920E-03
C	8.62891E+02	1	8.62891E+02	7.65358E+00
AB	1.50156E+01	1	1.50156E+01	1.33184E-01
AC	3.84400E+03	1	3.84400E+03	3.40951E+01
BC	7.22500E+01	1	7.22500E+01	6.40835E-01
ABC	5.43906E+01	1	5.43906E+01	4.82428E-01
REM	2.79604E+04	248	1.12743E+02	
TØT	4.75717E+04	255		

EXPERIMENT 2

MANUAL TOOLS

TABLE 12

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

1/2

SØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	3.51562E-02	1	3.51562E-02	2.38745E-04
B	2.34473E+02	1	2.34473E+02	1.59229E+00
C	3.19932E+03	1	3.19932E+03	2.17264E+01
AB	8.78906E-01	1	8.78906E-01	5.96861E-03
AC	2.09879E+03	1	2.09879E+03	1.42528E+01
BC	1.87348E+02	1	1.87348E+02	1.27227E+00
ABC	1.01602E+01	1	1.01602E+01	6.89972E-02
REM	3.65192E+04	248	1.47255E+02	
TØT	4.22501E+04	255		

TABLE 13

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

7/16

SØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	1.42979E+03	1	1.42979E+03	1.26212E+01
B	4.98789E+01	1	4.98789E+01	4.40297E-01
C	1.26914E+01	1	1.26914E+01	1.12031E-01
AB	2.44141E+00	1	2.44141E+00	2.15511E-02
AC	4.90875E+03	1	4.90875E+03	4.33312E+01
BC	3.12848E+02	1	3.12848E+02	2.76161E+00
ABC	4.98789E+01	1	4.98789E+01	4.40297E-01
REM	2.80946E+04	248	1.13285E+02	
TØT	3.48609E+04	255		

EXPERIMENT 2

MANUAL TOOLS

TABLE 14

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

3/8

ØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	2.15064E+03	1	2.15064E+03	1.30328E+01
B	2.37656E+01	1	2.37656E+01	1.44019E-01
C	5.34766E+02	1	5.34766E+02	3.24066E+00
AB	4.35766E+02	1	4.35766E+02	2.64072E+00
AC	5.00641E+02	1	5.00641E+02	3.03386E+00
BC	6.43891E+02	1	6.43891E+02	3.90195E+00
ABC	1.56250E-02	1	1.56250E-02	9.46368E-05
REM	4.09244E+04	248	1.65018E+02	
TØT	4.52139E+04	255		

Statistical Treatment of Experimental Results of Experiment 3: Hatch Test. The analysis of variance reflected an A x C interaction that was statistically significant at less than the .01 level. In addition, the main effects of cylinder mode (A) and subjects (C) were statistically significant beyond the .01 level. The main effect space-tool mitten (B) was not statistically significant. The data for the space mitten and tool mitten are combined and graphically presented in Figure 9 in the text. The analysis of variance table reflecting F ratios are found in this appendix, Table 15.

It can be noted from Figure 9 in the text that the relationship found for a decrement in performance resulting from the dynamic mode of the maintenance task cylinder is similar to that from Experiment 1. The data for the operator's performance with the space mitten and the tool mitten were combined due to the lack of a statistically significant difference between the performance of these two tools. This study tends to substantiate to some extent the findings from Experiment 1. The A x B interaction was in the same direction as that in test 1, i.e., the space mitten perfromed better than the tool mitten in the dynamic case, but in this experiment the difference was not statistically significant.

EXPERIMENT 3
HATCH
TABLE 15
A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER OF ØBSERVATIØNS PER CELL

ØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	4.91401E+05	1	4.91401E+05	2.44695E+02
B	6.24100E+03	1	6.24100E+03	3.10774E+00
C	8.02306E+04	1	8.02306E+04	3.99512E+01
AB	7.70006E+03	1	7.70006E+03	3.83428E+00
AC	3.15062E+04	1	3.15062E+04	1.56887E+01
BC	7.56900E+03	1	7.56900E+03	3.76902E+00
ABC	4.32306E+03	1	4.32306E+03	2.15269E+00
REM	1.12460E+05	56	2.00821E+03	
TØT	7.41431E+05	63		

<u>Experiment 4</u>: <u>Screwdriver</u>. The analysis of variance reflects a significant F ratio ($p < .01$) associated with the main effect tool type. The other main effects and interactions did not reflect a statistically significant F ratio. The difference between the space mitten and tool mitten needs to be interpreted with care since the tool mitten's voltage was reduced from 120 volts to 70 volts causing the tool mitten to operate considerably slower than it had during the previous experiments.

EXPERIMENT 4

SCREWDRIVING

TABLE 16

A THREE FACTØR ANALYSIS ØF VARIANCE PRØGRAM
WITH AN EQUAL NUMBER ØF ØBSERVATIØNS PER CELL

ØURCE	S.S.	D.F.	MEAN SQUARE	F RATIØ
A	6.43448E+03	2	3.21724E+03	6.38795E+01
B	2.05926E+01	2	1.02963E+01	2.04437E-01
C	4.84444E+01	8	6.05556E+00	1.20235E-01
AB	1.05593E+02	4	2.63981E+01	5.24145E-01
AC	1.71519E+02	16	1.07199E+01	2.12848E-01
BC	8.84074E+01	16	5.52546E+00	1.09710E-01
ABC	1.83741E+02	32	5.74190E+00	1.14008E-01
REM	4.07950E+03	81	5.03642E+01	
TØT	1.11323E+04	161		

Analysis of Variance for Two-Way Classification. This appendix describes the test variance according to the F-distribution. The F distribution has the property

$$\int_{0}^{\infty} h_{m_1,\, m_2}(F)\, dF = 1$$

such that the distribution $h_{m_1,\, m_2}(F)$ is the distribution of the ratio $F = \dfrac{u/m_1}{V/m_2}$ where u and V are statistically independent variables having χ^2 distributions with m_1 and m_2 degrees of freedom.

The data collected for this study was divided into mutually exclusive subgroups and classified by an arrangement corresponding to rows and columns, employing the notation that r is the number of rows, s is the number of columns and y_{ij} is any element in the array, then

$$\bar{y} = \frac{1}{rs} \sum_{i=1}^{r} \sum_{j=1}^{s} y_{ij}$$ is the general mean

$$\bar{y}_{i\cdot} = \frac{1}{s} \sum_{j=1}^{s} y_{ij}$$ is the mean of the i^{th} row

$$\bar{y}_{\cdot j} = \frac{1}{r} \sum_{i=1}^{r} y_{ij}$$ is the mean of the j^{th} column

The total sum of squares is then expressed as

$$S_T = S_{rows} + S_{columns} + S_{Errors}$$

Where:

$$S_R = s \sum_{i=1}^{r} (\bar{y}_{i.} - \bar{y})^2$$

$$S_c = r \sum_{j=1}^{s} (\bar{y}_{.j} - \bar{y})^2$$

$$S_E = \sum_{i=1}^{r} \sum_{j=1}^{s} (y_{ij} - \bar{y}_{i.} - \bar{y}_{.j} + \bar{y})^2$$

Then, if there is no variation of population within the row:

$$F = (S-1) \frac{S_R}{S_E}$$

And, if there is no variation of population within the column:

$$F = (r-1) \frac{S_C}{S_E}$$

In order to test the hypothesis that there is no significant difference in the results which can be attributed to the A X B interaction at the one percent level, table X in the <u>Hand Book of Probability and Statistics</u>, Burington and May, is employed with the significance level ϵ set at .01, $m_1 = S-1$ and $m_2 = (r-1)\ m_1$.

The values of m_1 and m_2 therefore establish the minimum value of F for significance at the one percent level.

SAMPLE CALCULATION OF VARIANCE

Experiment 1 involved a comparison of the tool and space mittens in the static and dynamic modes respectively. Listed below is the data collected for the 9/16 inch hex head bolt. The number in each cell represents the time in seconds required to perform the task for each of 6 subjects. The data listed in the four rows represent each of the trials performed by the six subjects.

TOOL MITTEN: STATIC: BOLT TIGHTENED

	S_1*	S_2	S_3	S_4	S_5	S_6
Trial 1	9	9	12	22	11	13
Trial 2	11	9	12	25	11	14
Trial 3	9	9	12	19	11	8
Trial 3	12	10	13	20	11	7

*Subjects 1 - 6.

TOOL MITTEN: DYNAMIC: BOLT TIGHTENED

	S_1	S_2	S_3	S_4	S_5	S_6
Trial 1	46	51	31	38	48	31
Trial 2	20	42	50	28	41	12
Trial 3	25	47	26	46	27	29
Trial 4	19	42	30	42	26	30

SPACE MITTEN STATIC: BOLT LOOSENED

Trial 1	17	15	16	22	10	14
Trial 2	15	11	15	21	9	16
Trial 3	15	11	10	43	10	12
Trial 4	21	12	11	29	9	9

SPACE MITTEN:DYNAMIC: BOLT LOOSENED

Trial 1	17	22	32	13	28	16
Trial 2	25	18	36	10	24	13
Trial 3	21	23	29	11	21	20
Trial 4	19	18	27	10	20	12

These four arrays are represented by a 6 x 4 matrix.

Calculation of the F ratio was performed on a GE 235 computer. The print-out on the following page provides under the headings of:

Source of variance

- A - Maintenance Cylinder Mode: static - dynamic
- B - Space Mitten - Tool Mitten
- C - Number of Experimental Trials
- S.S. - the sum of the squares
- D.F. - the degrees of freedom

With 1 and 90 degrees of freedom (approximately 1.95), an F ratio needs to exceed 6.95 so as to be statistically significant at the 1 percent level, or 3.95 at the 5 percent level.

The attached computer read-out indicates statistically significant F ratios of the main effects A and B, and the interaction A x B.

A THREE FACTOR ANALYSIS OF VARIANCE PROGRAM
WITH AN EQUAL NUMBER OF OBSERVATIONS PER CELL

SOURCE	S.S.	D.F.	Mean Square	F RATIO	
A	4.63426E+03	1	4.63426E+03	7.18513E+01	XX
B	9.06510E+02	1	9.06510E+02	1.40549E+01	XX
C	1.52115E+02	3	5.07049E+01	7.86147E-01	
AB	2.04426E+03	1	2.04426E+03	3.16950E+01	XX
AC	1.11781E+02	3	3.72604E+01	5.77700E-01	
BC	5.68646E+01	3	1.89549E+01	2.93883E-01	
ABC	4.51146E+01	3	1.50382E+01	2.33158E-01	
REM	5.15983E+03	80	6.44979E+01		
TOT	1.31107E+04	95			

XX significant at $p < .01$